Characterizing and Improving Spatial Visualization Skills

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ABSTRACT

Three-dimensional spatial visualization is an essential skill for geoscientists. We conducted two evaluations of students' spatial skills to examine whether their skills improve after enrollment in a geology course or courses. First, we present results of pre- and post-course survey of abstract visualization skills used to characterize the range of spatial abilities in the student population at Carleton College. In Introductory Geology, there was a correlation between those who score very poorly on the spatial survey and those who receive a grade of C or lower. Students in higher-level courses had better developed visualization skills than those in Introductory Geology. Gender differences disappeared in upper-level courses except for the spatial relations (mental rotation) task, where male students consistently outperformed females. Second, we describe the efficacy of instructional materials designed for a Structural Geology course at the University of Wisconsin. This study included a qualitative controlled experiment investigating whether frequent use of stereographic projections affected student performance on exam questions requiring spatial skills. The results of both the survey-based quantitative study and materials-based qualitative study suggest that students' spatial abilities can improve through practice provided in geology courses.

INTRODUCTION

Three-dimensional spatial visualization is an extremely important skill in many fields involving science, technology, engineering, and mathematics, including the geosciences. For example, geologic structures like faults and folds are inherently three-dimensional features; successful students must be able to visualize how these structures interact with topography, are represented on geologic maps, and extend to depth in the subsurface. Despite the importance of spatial visualization in many fields, it is rarely taught thoughtfully (Mathewson, 1999) or tested for (Humphreys et al., 1993) in K-12 or undergraduate curricula. Consequently, many talented students whose spatial visualization skills are insufficient to accomplish course assignments do poorly in visualization-intensive classes and switch their field of study away from these disciplines (Shea et al., 2001; Sorby, 2001). This process results in an unfortunate homogenization of thinking styles among students in these disciplines and may result in a lack of novel ideas and problem-solving strategies in fields that rely heavily upon innovation.

Some students are naturally better at spatial visualization than others (Lord, 1985; Kali & Orion, 1996; Piburn et al., 2002). This range of natural ability often leads to frustration in the class for both students and instructors. Students whose spatial skills are naturally inferior to others' often feel frustration at being unable to complete tasks that are easy for others. Similarly, an instructor must interact with a diverse group of students whose different abilities may not allow them all to have the same opportunity to perform well on assignments and exams, through no lack of effort or interest on the students' part. Research has shown, however, that people's spatial visualization skills can often improve with practice (Lord 1985, 1987; Piburn et al., 2002).

The main purpose of this project was to test whether students' three-dimensional visualization skills can be improved through practice provided in geology courses. We used two different strategies on two different student populations to answer this question. We present the results of each study below, following a discussion of spatial visualization.

SPATIAL VISUALIZATION

Spatial visualization is a complex process that involves both visual abilities and the formation of mental images (Mathewson, 1999). Because of the importance of spatial visualization across many disciplines, it has been studied by a wide variety of workers in science, education, and cognitive psychology. Various classification schemes exist for spatial visualization, many of which divide the process of visualization into anywhere from three (e.g. Ekstrom et al., 1976; Linn and Peterson, 1985) to ten component skills (Lohman, 1988). Often these component skills overlap, making the terminology confusing.

We use a simple division of spatial visualization into three component skills useful in a geological context: spatial relations, spatial manipulation, and visual penetrative ability. (For an alternate approach, see Kastens and Ishikawa (2006) where geologic tasks are subdivided and the cognitive skills required for each task are discussed.) *Spatial relations* (Shepard and Cooper, 1982) is the ability to mentally rotate an object about its center (Fig. 1a). Rotations may be about one or more axes (Shepard and Metzler, 1970) and can reflect a variety of geological problems on all scales, from crustal block rotations to plotting fault orientation data on a stereonet. *Spatial manipulation* (termed spatial orientation by Ekstrom et al., 1976) is the ability to mentally manipulate an image into another arrangement (Fig. 1b). Spatial manipulation skills are useful in structural geology when envisioning how bodies of rock deform through time, such as migration of a magma body through the crust, or progressive folding of a stratigraphic succession. *Visual penetrative ability* (Kali and Orion, 1996) is the ability to mentally imagine what is inside of a solid object (Fig. 1c). This skill is less commonly included in many visualization classifications, but is critical for geoscientists who commonly use cross sections, thin sections, roadcuts, and

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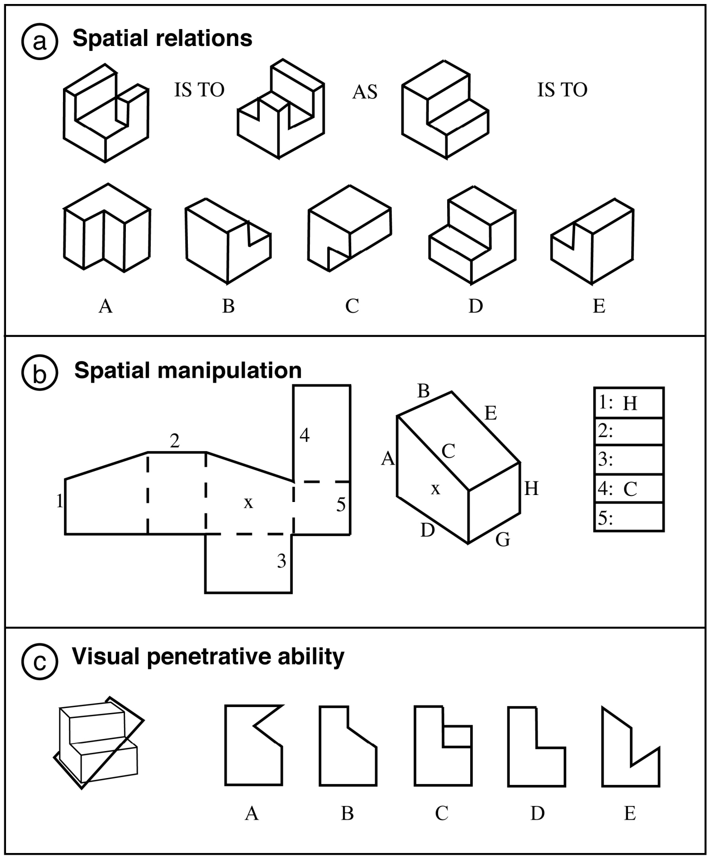


FIGURE 1. Examples of spatial visualization component skills. In (a), which tests spatial relations, students must decipher the rotation performed to the first object and perform the same rotation to the second object. They then choose the correct rotated configuration of the second object. From Guay (1976). In (b), which tests spatial manipulation, students must mentally transform the two-dimensional polygon on the left, by folding it along the dotted lines, into the three-dimensional shape on the right. They must then match up the numerical sides of the unfolded shape with the alphabetical sides in the folded shape. From Ekstrom et al. (1976). In (c), which tests visual penetrative ability, a three dimensional object is sliced by a plane. Students must determine what the intersection between the object and the slicing plane looks like when viewed orthogonal to the surface.

many other slices through Earth and Earth materials to interpret geologic processes and histories.

Numerous studies have shown that practice tends to improve all students' spatial visualization skills regardless of their initial ability (e.g. Lord, 1987; Sorby, 2001; Piburn et al., 2001). Participation in courses with occasional exposure to spatial exercises, including geology (e.g. Orion et al., 1997) seems to improve spatial visualization skills. More directed interventions using software, handheld objects, and mental imagery practice also improve students' skills. Geologically relevant examples include a study by Lord (1985), who found that students given 30 minutes of weekly practice mentally bisecting three-dimensional geometric figures significantly improved their spatial visualization abilities, including their spatial relations and visual penetrative ability component skills. Duesbury and O'Neil (1996) used computer-generated two and three-dimensional images to test whether these images aided three dimensional visualization ability. Practice was given to two groups, one of which allowed for rotation of the images. The authors found that the rotational group performed significantly better on measures of spatial ability. In a controlled study, Piburn et al. (2001) showed that students who received computer-based instructional modules about three-dimensional topics related to geology were better able to solve spatial visualization problems. Other examples of the benefits of practice with spatial visualization skills exist for fields including chemistry (e.g. Harrison and Treagust, 2000; Wu et al., 2001; Wu and Shah, 2004), mathematics (e.g. Steen, 1990; Loeb, 1992; Emmer, 1993), and geography (MacEachren, 1995).

There is active debate in the literature whether gender plays a role in spatial visualization ability. Some studies, typically of abstract spatial tasks, have shown that males tend to outperform females on spatial tasks (Newcombe et al., 1983; Berfield et al., 1986; Lord 1987; Orion et al., 1997; Coleman and Gotch, 1998; Sorby, 2001) but these differences may be due to environmental conditions (Newcombe and Dubas, 1992; Baenninger and Newcombe, 1995; Levine et al., 2005). Other studies suggest that females have better abilities on certain component spatial tasks (e.g. Linn and Petersen, 1985; Self et al., 1992; Self and Golledge, 1994; Dabbs et al., 1998). In geology, Piburn et al. (2001) suggest that gender differences can be eliminated by allowing ample opportunities for practice. Although our study does not directly focus on determining if there are gender differences in spatial abilities of geology students, some of our data allow us to comment on this topic.

CONTEXT FOR THE STUDIES

We present results from two separate studies: the first from Carleton College and the second from the University of Wisconsin. The Carleton College study used pre- and post-course surveys from introductory, intermediate, and upper-level geology courses to establish a baseline understanding of students' visualization skills and how their skills change after enrollment in geology courses. These survey data allow exploration of the differences in the student population among men and women as well as majors and non-majors. The University of Wisconsin study was a qualitative study on a small number of students taking Structural Geology at the University of Wisconsin. Students were asked to solve geologically relevant problems that required spatial visualization skills and several assessment strategies were employed to test whether students' skill improved. Both studies were designed to test whether visualization practice provided in geology courses could improve students' visualization skills.

The Carleton College study is presented first because this dataset provides a picture of students' abilities in a range of geology courses. Chronologically, however, this study took place after our University of Wisconsin study. Although this second study is qualitative – the small class

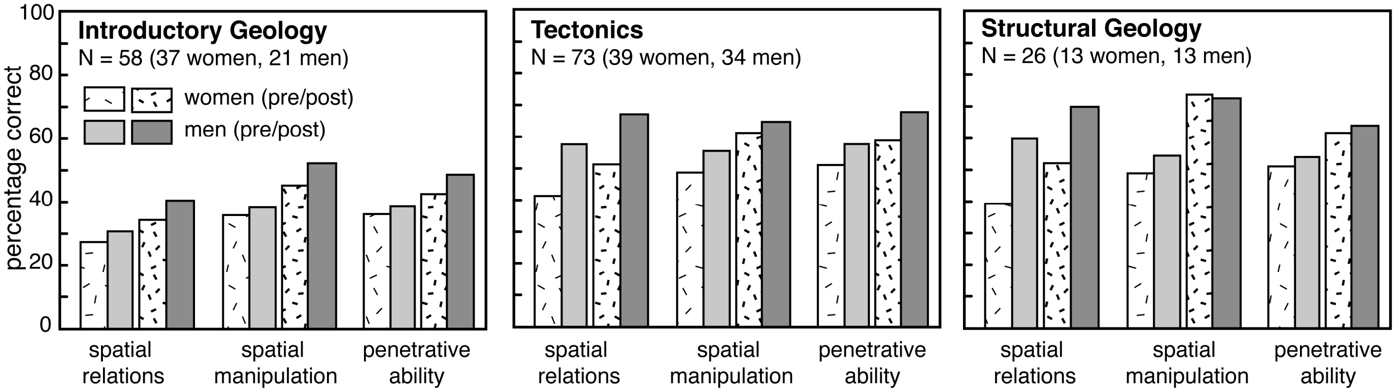


FIGURE 2. Results from pre- and post-course abstract visualization survey from Carleton College students from three separate courses. These have been divided based on three component skills – spatial relations, spatial manipulation, and visual penetrative ability – and the average scores of women and men have been shown.

size prohibited reliable quantitative analysis – the Wisconsin dataset provides insight about the types of problems students have when solving geologically relevant problems (as opposed to abstract spatial problems) and represents a model for how geoscience educators might test their own instructional materials. We therefore present both studies (out of chronological order) relying primarily on the quantitative results but noting pertinent aspects of the qualitative study when they are especially informative.

QUANTITATIVE STUDY: CARLETON COLLEGE

The first study we describe explores students' abilities to solve abstract visualization problems. We developed an abstract visualization survey and administered this as a pre- and post-course survey to students in Titus' courses at Carleton College. This survey-based design allows us to examine differences across the student population and gain more quantitative information about students' spatial skills. The disadvantage, however, is that we do not know how performance on abstract visualization tasks transfers to the ability to solve applied geology problems requiring spatial skills.

Survey design

The survey instrument is divided into three sections, each of which tests a particular component skill: spatial relations, spatial manipulation, and visual penetrative ability. A problem from each section is illustrated in Figure 1. The first section consists of ten three-dimensional rotation exercises from a longer and widely used (e.g. Sorby, 2001; Black, 2005; Sibley, 2005) spatial test for mental rotation published by Guay (1976). (In an earlier version of the survey administered at the University of Wisconsin, we used a two-dimensional rotation task from Ekstrom et al. (1976) that was too easy for college students.) The second section consists of four spatial manipulation exercises published by Ekstrom et al. (1976). The third section consists of fifteen penetrative thinking exercises we created in addition to some published by Crawford and Burnham (1946) and Myers (1953). We designed the survey to minimize the amount of class time necessary, thus each section lasts three minutes and the total time for administering the test is no more than fifteen minutes. Most students do not finish each section although some students are able to finish individual sections.

This survey was administered to Titus' students at Carleton College on the first and last days of three separate courses – Introductory Geology, intermediate-level Tectonics, and upper-level Structural Geology – taught from Fall 2006 through Fall 2008. All courses were taught in the mornings and each had a four-hour afternoon lab associated with the course. Data from the same courses from different years were combined to improve statistics: two years of Introductory Geology (N = 20; N = 40), three years of Tectonics (N = 32; N = 14; N= 37), and two years of Structural Geology (N = 15; N =11). Specific exercises (i.e. the skill puzzles described in a later section) were used in each course to allow students to practice with spatially-intensive problems. The nature of course material in Tectonics and Structural Geology required spatial problem solving more often than in Introductory Geology.

Below, we highlight selected results of these surveys including differences between the three courses, between men and women, and between majors and non-majors. We also compare survey scores in Introductory Geology with final course grades.

Survey results

Course comparisons

The average scores on the pre- and post-course survey are illustrated in Figure 2 for all three courses. Table 1 also summarizes the p-values or the pre- and post-course survey analysis. For each of the three tasks in the survey, there is marked improvement between the pre- and post-course survey, which is always statistically significant with $p < 0.05$. Between courses, there is also general improvement in scores, where higher percentages are observed in higher-level courses. These intermediate- and upper-level courses more consistently require visualization skills to understand course content and are typically only taken by majors or potential majors.

TABLE 1. SUMMARY OF PRE- AND POST-COURSE SURVEY OF ABSTRACT VISUALIZATION ABILITIES FROM COURSES AT CARLETON COLLEGE[1]

Carleton College Course	spatial Relations		spatial manipulation		penetrative ability	
	pre-test	post-test	pre-test	post-test	pre-test	post-test
Introductory Geology						
all (N=58)	<0.01		<0.01		<0.05	
women (N=37)	<0.01		<0.05		0.12	
men (N=21)	<0.05		<0.01		<0.05	
gender compare	0.60	0.32	0.75	0.35	0.71	0.41
non-majors (N=43)	<0.05		<0.01		<0.01	
majors (N=15)	<0.05		<0.01		0.103	
group compare	0.26	0.09	0.30	0.30	0.17	0.003
Tectonics						
all (N=73)	<0.01		<0.01		<0.01	
women (N=39)	<0.01		<0.01		<0.05	
men (N=34)	<0.01		<0.01		<0.01	
gender compare	<0.01	<0.01	0.33	0.55	0.19	0.11
Structural Geology						
all (N=26)	<0.01		<0.01		<0.01	
women (N=13)	<0.05		<0.01		<0.05	
men (N=13)	<0.05		<0.01		0.07	
gender compare	<0.05	0.05	0.59	0.91	0.72	0.74

[1] P-values assess significance of changes between pre- and post-course surveys for several sub-populations, including women, men, non-majors, and majors; inter-gender and major/non-major comparisons are also made for each spatial task on both the pre- and post-course surveys.

Gender comparisons

The results in Figure 2 and Table 1 are also divided by student gender. In Introductory Geology, men outscore women on all three tasks on the pre- and post-course surveys. However, differences between genders are not statistically significant and women typically score above the pre-course survey levels of their male counterparts on the post-course survey. In Tectonics and Structural Geology, the pattern is similar but these courses attract students who are considering or are geology majors. Students' overall scores are higher than those in the Introductory Geology course and statistically significant gender differences are observed only for the spatial relations (mental rotation) task. In contrast, there are no differences between gender for the spatial manipulation or visual penetrative ability tasks.

Similar gender differences can also be observed in Figure 3, which shows results compiled from the 28 students who have taken the visualization survey four times as a result of taking two of the three possible courses. These students are all likely geology majors. The gains between the first and fourth exams are all significant with $p < 0.01$. Perhaps more importantly, the differences between men and women are completely absent from the spatial manipulation and visual penetrative ability tasks. In fact, women outscore men on three of the four surveys for visual penetrative ability. The differences for the spatial rotation task, however, are still apparent (although not statistically significant given this smaller sample size).

Majors versus non-majors

From the pool of students who have taken Introductory Geology, we compared those who have not yet taken another geology class (and probably will not)

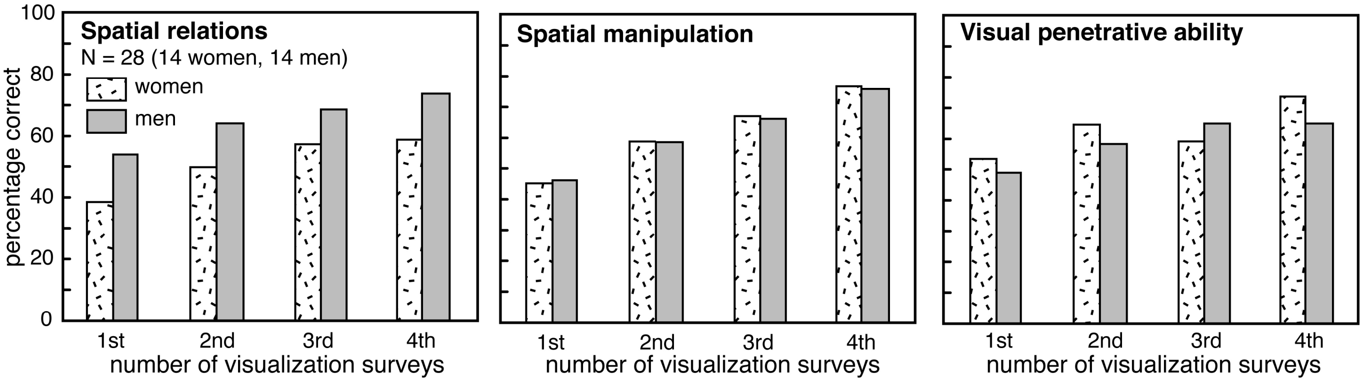


FIGURE 3. Results from pre- and post-course abstract visualization surveys taken by Carleton students three or four times. The left panel shows the results from the spatial relations task, the middle panel from the spatial manipulation task, the right panel from the visual penetrative ability task.

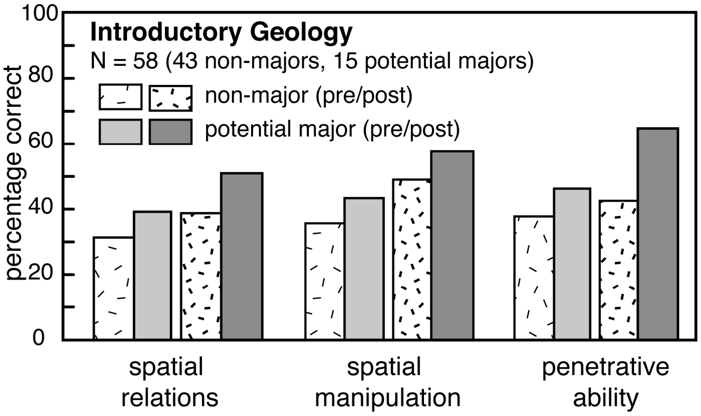


FIGURE 4. Results from pre-/post abstract visualization survey of Introductory Geology students comparing the scores of those who have not taken a second geology class (likely non-majors) to those considering a geology major (potential majors).

with those who have taken or are signed up for a second geology course in Figure 4. Most of these differences are not statistically significant (Table 1) in part because of the smaller sample size of the potential major group. However, our small dataset suggests that potential majors outscore non-majors on both pre- and post-course surveys, that potential majors have increased gains between surveys, and that non-majors do not reach the pre-course survey level of their potential major counterparts.

We also compare survey scores from students in Introductory Geology to their final course grades in Figure 5. Although there is significant scatter in this dataset, students receiving higher grades tend to score higher on the three abstract visualization tasks. This interpretation is supported in two distinct ways. First, students who earned a B+ or above had scores > 10% on the post-survey for each of the three tasks (see the "hole" in the lower right corner of each graph). Second, students who earned Cs had lower visualization scores in general (typically not scoring > 60% on any section) and those two students who failed the course had particularly low scores (< 50%). It is worth nothing, however, that very low scores on any of the three tasks is not an absolute predictor of poor course performance as several students who received grades as high as B scored very poorly (< 10%) on one or more of the abstract visualization tasks.

QUALITATIVE STUDY: UNIVERSITY OF WISCONSIN STUDY

Over several semesters, we developed instructional materials to provide students with practice using spatial visualization skills in introductory and upper-level geosciences courses at the University of Wisconsin. Here we describe in detail an implementation of those materials in a 2005 Structural Geology course. Structural Geology is a highly visual discipline that aims to observe and understand the processes and implications of rock deformation. Developing a thorough understanding of rock deformation often involves mentally projecting, rotating, and generally manipulating spatial data. The fourteen students enrolled in this course were all upper-class majors in geology or geological engineering.

Our instructional materials were implemented in two ways: (1) data visualization exercises were given in a controlled study in the laboratory portion of the class (the seven students in each lab section represented the experimental and control group) and (2) geologically relevant exercises involving component visualization skills were given to all students in the lecture portion of class. To evaluate the effectiveness of our materials, we compare answers on exams from the experimental and control groups as well as a voluntary survey six months after the end of the course. Even though quantitative assessment of our instructional materials is not possible given the small number of students enrolled in the course, the results of this experiment are promising. Further, we offer our approach as a model for geoscience educators interested in assessing the effectiveness of particular teaching strategies or materials (and conclude with ideas on what types of pitfalls could be avoided by careful experimental design).

Laboratory exercises

The first set of instructional materials for this study at

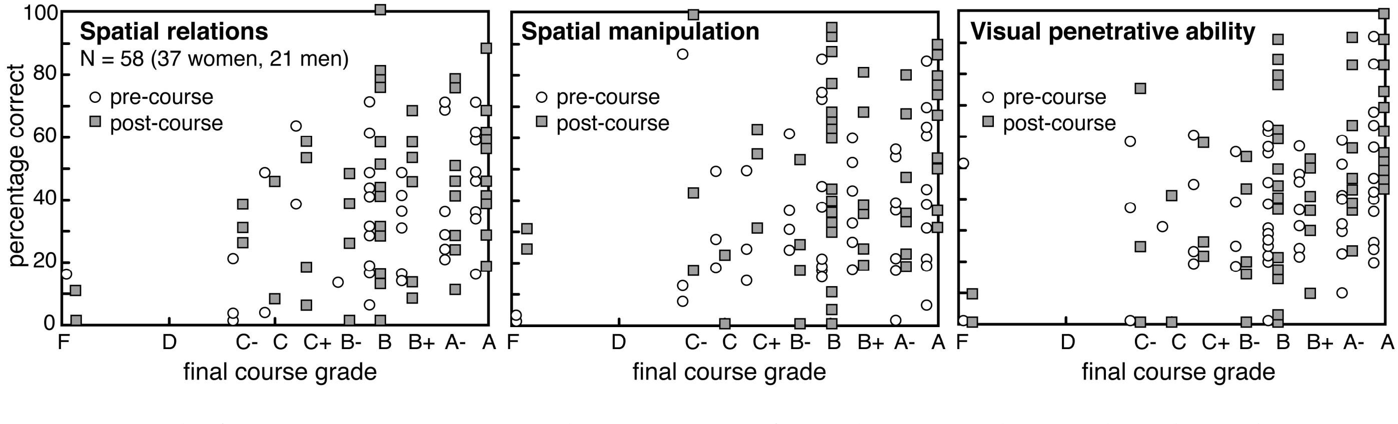
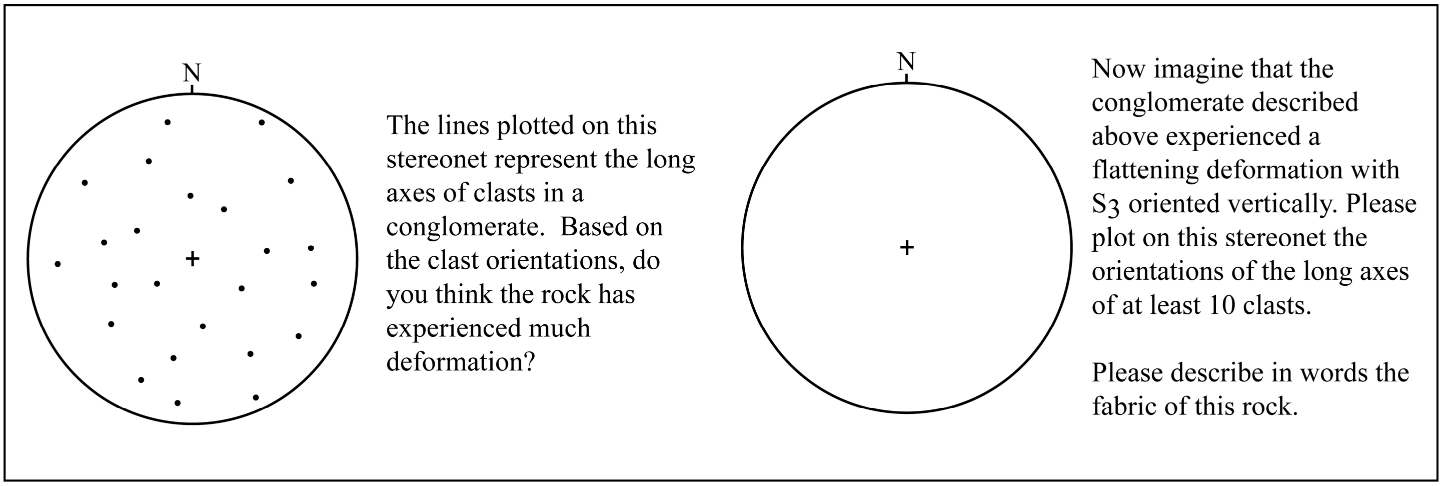


FIGURE 5. Results from pre-/post abstract visualization survey of Introductory Geology students (N = 58) comparing their scores versus their final grade. Note that the pre-course survey scores have been offset slightly to the left of the post-course survey scores to facilitate easier comparisons. Because of our scoring system, it is possible to have a negative score on the sections of the survey – we rounded these negative scores to zero.



The lines plotted on this stereonet represent the long axes of clasts in a conglomerate. Based on the clast orientations, do you think the rock has experienced much deformation?

Now imagine that the conglomerate described above experienced a flattening deformation with S_3 oriented vertically. Please plot on this stereonet the orientations of the long axes of at least 10 clasts.

Please describe in words the fabric of this rock.

FIGURE 6. Example of a stereographic projection puzzle used in the laboratory portion of Structural Geology in the University of Wisconsin experiment.

the University of Wisconsin was designed to provide practice with stereographic projection, a common visualization tool in Structural Geology. In our experience, stereographic projections are often difficult for students. Consequently, we hypothesized that if stereographic projections could be mastered, they might serve as a gateway into more complicated visualization problems.

Implementation

There were two laboratory sections in this course, which met at the same time of day on consecutive days and were taught by the same graduate student TA (either Horsman or Titus) in any given week. We conducted a small-scale controlled experiment in which the experimental section received stereonet-related problems while the control section did not. Possible answers were discussed immediately following the exercise and the instructor offered insight into how an expert might solve each problem. For the experimental group, 10-15 minutes of each lab session were devoted to solving and discussing a stereonet-related exercise.

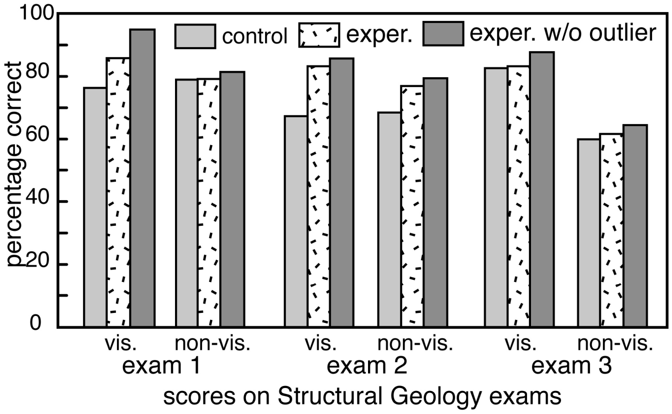


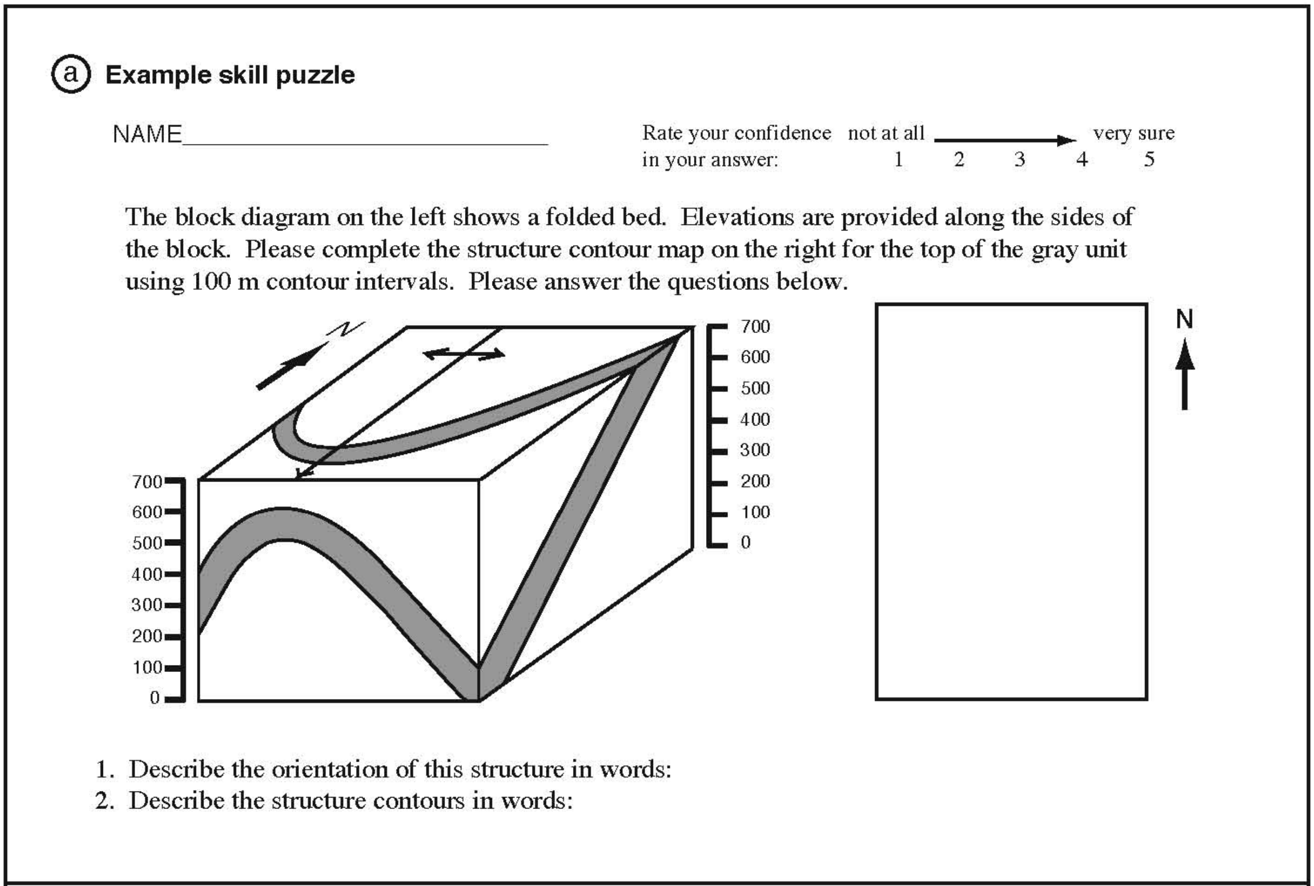
FIGURE 7. Student scores on exams in the University of Wisconsin study. Scores are divided into visualization (vis.) and non-visualization (non-vis.) questions. Three groups are compared: the control group, the experimental group (exper.) and the experimental group without one outlier student (exper. w/o outlier).

An example stereographic projection exercise is shown in Figure 6. Our exercises emphasize practical spatial visualization skills in geology including: (1) extracting and/or plotting three-dimensional data on a stereonet, (2) recognizing the difference between linear and planar data, (3) estimating where data would plot on a stereonet without using technical methods, (4) describing and/or generalizing stereonet data in words, (5) rotation of stereonet data about different axes, (6) application of stereonets to straightforward geologic problems on a variety of spatial scales, and (7) application of stereonets to more abstract and complicated geologic problems. However, recognizing that students have a variety of preferred learning styles (e.g. Tanner and Allen, 2004 and references therein), there were several different types of activities to address different learning styles including written independent assignments, oral descriptions of problems, and group activities with tactile objects.

Effectiveness

We used student performance on exams to assess the effectiveness of this mini controlled experiment. Students had three exams during the semester; for each, we designed questions to specifically test spatial visualization skills, including a stereonet exercise within a multi-step visualization question.

Figure 7 shows a comparison of exam scores between the experimental and control groups. On the first two exams, the experimental group outperformed the control group on visualization problems (especially after the removal of one outlier student who performed particularly poorly in all aspects of this course). For the non-visualization questions, there was no difference between the two groups of students on these two exams. For the third exam, the difference between groups disappeared. However, for this exam, students were told that if their score was better than their three-exam average, it would count as their exam score for the entire course. This may have encouraged students to study more



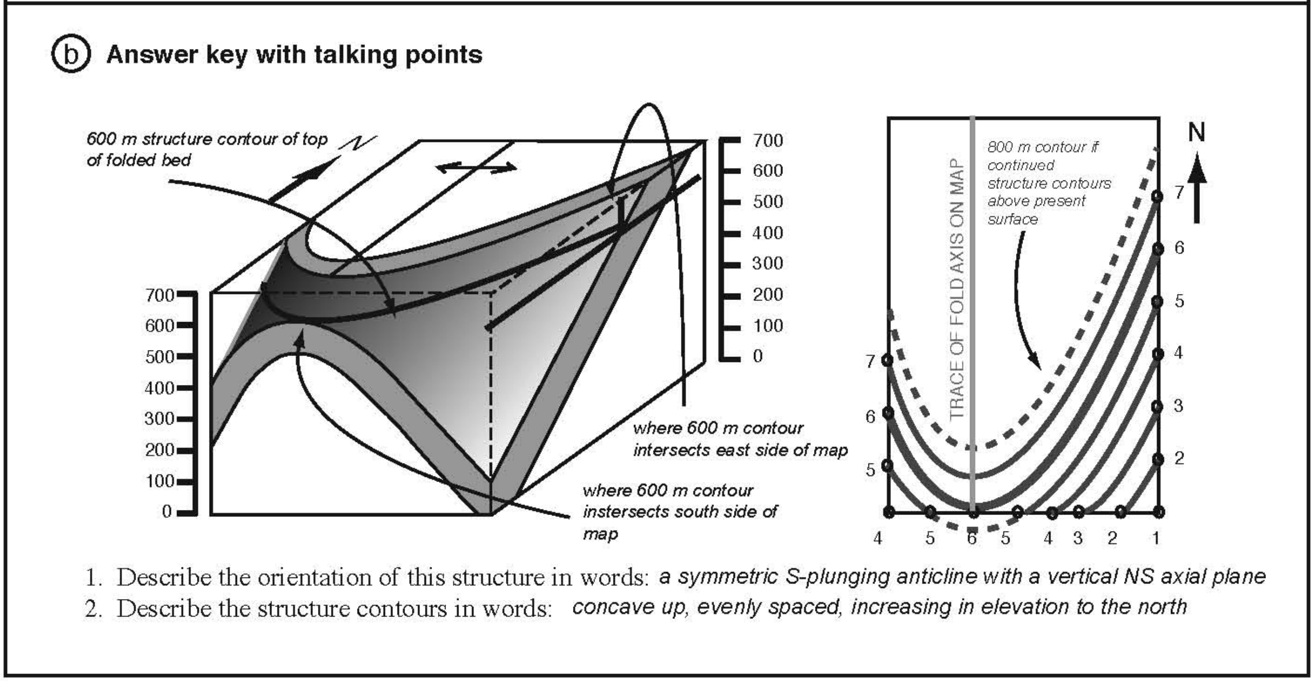
ⓐ **Example skill puzzle**

NAME_____________________________

Rate your confidence in your answer: not at all → very sure
1 2 3 4 5

The block diagram on the left shows a folded bed. Elevations are provided along the sides of the block. Please complete the structure contour map on the right for the top of the gray unit using 100 m contour intervals. Please answer the questions below.

1. Describe the orientation of this structure in words:
2. Describe the structure contours in words:



ⓑ **Answer key with talking points**

1. Describe the orientation of this structure in words: *a symmetric S-plunging anticline with a vertical NS axial plane*
2. Describe the structure contours in words: *concave up, evenly spaced, increasing in elevation to the north*

FIGURE 8. Example of a skill puzzle used in the lecture portion of Structural Geology where (a) shows the student version and (b) shows the key used for discussion following completion.

diligently for Exam 3 than for earlier exams. Further, it is interesting to note that for the third exam all students did better on the visualization questions than they did on non-visualization questions. This may be linked to the lecture-based activities that all students received described in the following section.

Lecture exercises

To give students practice developing their visualization skills within a geological context, we also developed a set of formal assessment tools that we call *skill puzzles* for use in the classroom part of Structural Geology (for all fourteen students). The rationale for these exercises came from a pilot study in the previous Structural Geology course in 2004, where students were asked to solve problems that required spatial skills, such as making structure contour maps or drawing cross-sections from block diagrams similar to those used by Kali and Orion (1996). These spatial topics had been covered (at what we thought was extensive detail) in a prior course. However, we found that most students were unable to solve what were simple problems for the professor and TAs. The idea of skill puzzles grew out of our pilot exercises and were designed to provide more practice solving spatial problems with content pertinent to course topics.

Implementation

An example skill puzzle is shown in Figure 8. Students solved (anonymously) one skill puzzle per week during lecture. Each skill puzzle required some visualization skill to solve a geological problem relevant to the lecture material. Typical topics covered included: (1) interpreting topographic and geologic maps, (2) making geologic maps and cross-sections, (3) making and interpreting structure contour maps, and (4) stress and strain analysis.

Immediately following the exercise, the instructor and students engaged in a discussion of possible answers to the skill puzzle. This discussion included a description of how an expert might solve the problem. The total time devoted to both problem solving and discussion was usually 10 minutes. However, on at least one occasion, the discussion ended up generating questions that lasted considerably longer, revealing areas where more formal instruction was clearly necessary.

Effectiveness

Skill puzzles are first and foremost useful for diagnosing whether particular students have trouble with particular visualization component skills. In Figure 9, we show example answers to a cross-section-based skill puzzle, where visual penetrative ability is required. About half of the students in Structural Geology solved this problem correctly (and their answers are not shown). The other half had a variety of visualization problems ranging from (i) not recognizing the fault to (ii & iii) not understanding that the fault must cut through the entire cross-section. If the fault was recognized, it was (iv & v) curved instead of planar or (vi) the student did not realize that the rocks below the fault were also folded. Interestingly, those who correctly identified the fault (the bottom row) but incorrectly identified its geometry also felt compelled to label their fault with text. In contrast, those students who answered correctly did not use text in their solutions.

We also developed scoring rubrics (from 0 to 5 points) for each skill puzzle based on the type of question and component skills needed to answer the question. To examine whether our mini-controlled experiment affected skill puzzle scores, Figure 10 shows the average scores for students in the experimental and control groups. The experimental group typically outperformed the control group but this difference is not statistically significant. In fact, the variety of puzzle types, changing difficulty levels, and changing student attendance rates make it difficult to demonstrate any significant trends in students' abilities (experimental or control group) to solve skill puzzles.

A more concrete measure of improvement can be seen in the results from giving students the same skill puzzle twice: once at the start of the semester and again as a bonus question on the final exam (Fig. 11). In this example, there was a marked improvement in students' ability to determine the general shape and orientation of the structure contours for the folded layer – from an average of about 48% correct to 72% correct. We cannot specifically determine whether this improvement is due to real gain or whether students remembered the in-class discussion of the answer. However, because several answers on the final exam were actually more correct than the solution shown in class (because their structure contour lines continue across the entire map area), we suspect that most students actually developed a deeper understanding on this type of visualization-intensive problem.

Post-course survey

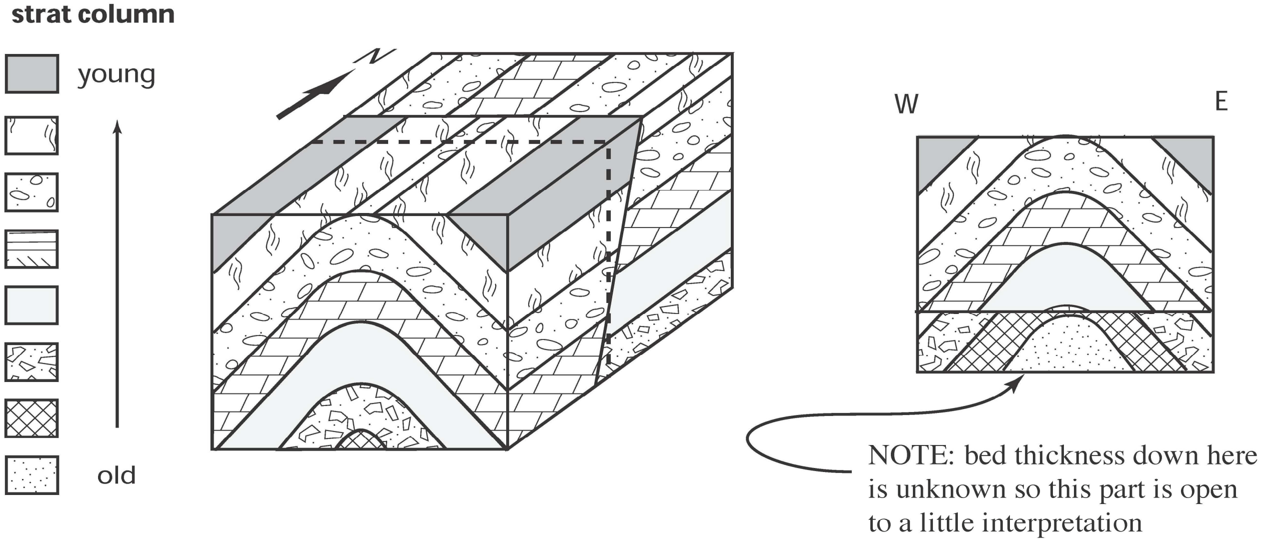
Six months after the end of the course we sent students several visualization questions and asked them to return the completed problems to us. The problems included visualization-related course material and tested skills like plotting information on stereonets. The intention of this survey was to examine long-term retention of visualization skills in the class as a whole and also to look for differences in retention between the test and control groups.

The sample size was especially small for the post-course follow-up exercises. We received completed exercises from 7 of the 12 students to whom we sent the voluntary work (4 students from the test group and 3 from the control group). Despite the small number of responses, some trends are apparent in the students' answers. All students retained basic stereonet plotting skills and were able to make accurate meaningful interpretations of basic structural information (e.g. fold orientation analysis) recorded on stereonets. Students' retention of more complicated structural analysis techniques (e.g. interpreting stress/strain orientations) was more limited – some students were still proficient and others were not. Both retention and performance by test group students appears to be superior to those of control group students, although the small sample size precludes statistical verification.

Suggestions for geoscience educators

While our results are qualitative, they suggest that practice can improve students' spatial skills, which itself is a promising finding for geoscience educators. Based on the controlled experiment, students in the experimental

ⓐ **Skill puzzle with key**



NOTE: bed thickness down here is unknown so this part is open to a little interpretation

The block diagram shows some folded stratigraphy that has been faulted. Notice that the fold hinge is horizontal - the fold is not plunging. Please sketch in the box on the right a cross setion through the block - the dotted line indicates the location of the cross section. The area's stratigraphy is shown in the stratigraphic column.

ⓑ **Sample answers**

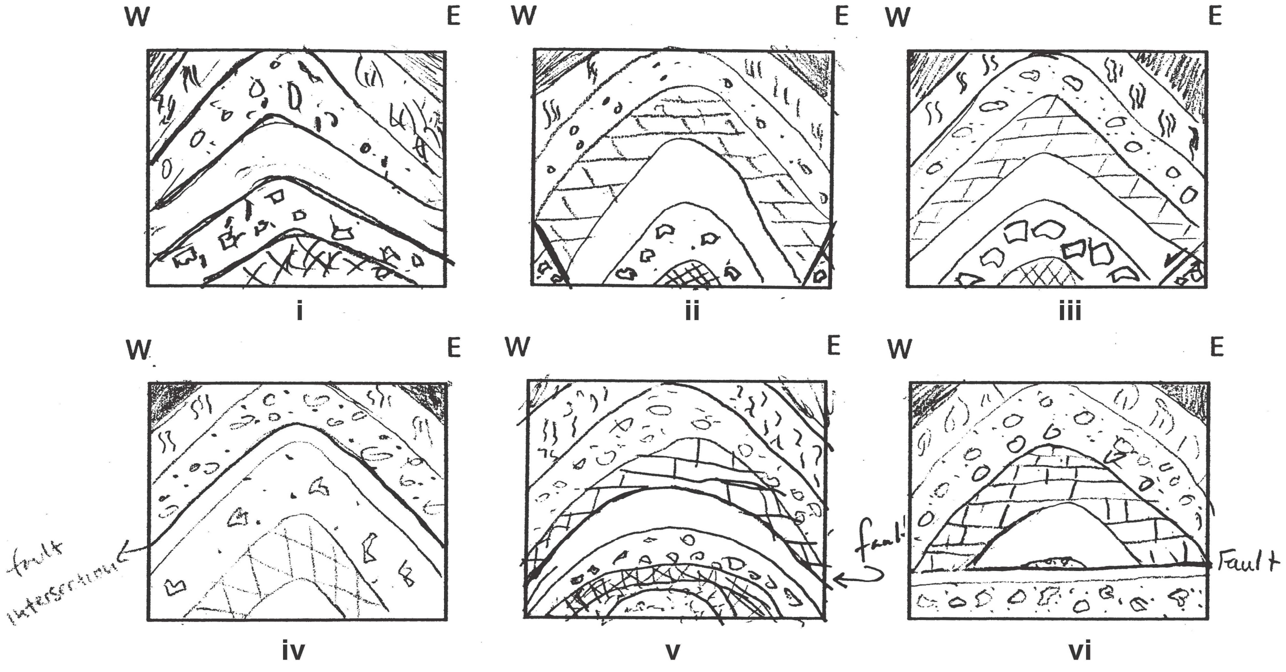


FIGURE 9. (a) Example of a skill puzzle used in the lecture portion of Structural Geology where (a) shows the puzzle and its key (the student version would have a blank cross-section) and (b) sample student answers demonstrating problems with visual penetrative ability.

group received more practice and they also typically outscored the control group on exams and skill puzzles. Based on the lecture exercises, all students tended to do better on visualization problems by the third exam than they did on non-visualization problems (Fig. 7). Thus, a limited amount of time devoted to practice and discussion of visualization problems in class (as little as 10 minutes per week) may significantly affect students' spatial skills.

Iterative development of these materials and methods, in addition to resources about classroom assessment (e.g. Angelo and Cross, 1993) taught us a great deal about the scholarship of teaching. What we discuss here, however, are several factors that we wished we had known at the start of this experiment. First, assessment of materials should not only occur in exam situations. Many students find exams to be stressful, a condition that can affect their ability to perform tasks that would otherwise be straightforward for them (Hembree, 1988; Hancock, 2001). For this reason, exam results should be used along with other, non-high-stakes tools to evaluate student performance. Second, this independent measure of student improvement might include a non-graded assessment administered as a pre- and post-course survey (such as the one used in the Carleton College study). In our University of Wisconsin study, we incorporated this into our study design by giving an abstract visualization test with questions similar to those shown in Figure 1. However, some sections of our test were too easy for college students and everyone answered them correctly. We also gave unlimited time on this survey, which removed differences between students who could solve problems with ease (and therefore likely have better-developed visualization skills) with those who used up to ten times as long to solve the same problems. Third, because our controlled experiment provided more time-on-task for students in the experimental group, we cannot determine whether their gains are due to this additional (yet small amount of) time and not necessarily to the instructional materials themselves (Ericsson et al. 1993). In a subsequent, more nuanced investigation we provided a control group with abstract visualization skill puzzles while the experimental group worked on skill puzzles with geologic context. This dataset, like the one presented in more detail here, also suffered from small sample sizes and the results are therefore not presented here. Last, collecting data over several years would help alleviate the problems of small sample sizes for those interested in assessing materials at institutions with small course enrollments.

DISCUSSION

The Carleton College data provide us with a better understanding of the range of students' abilities at a variety of points within a geology curriculum. In aggregate, students in Introductory Geology have less well-developed spatial visualization skills than those in higher-level courses. Those whose natural ability is high at the start of Introductory Geology are likely to be among the pool of students expected to continue in geology. Those who perform extremely poorly on the pre-course survey might be singled out for extra attention throughout the course to improve their chances of understanding course material and passing the class. In courses with both potential majors and majors (introductory and intermediate-level courses), visualization skills are better developed among all students and gender difference are only apparent for the spatial relations (mental rotation) task, consistent with a meta-analysis of spatial visualization skills by Linn and Peterson (1985). These results suggest that mental rotation should not be used as the only diagnosis for success at visualization abilities – additional component visualization skills must also be assessed.

The instructional materials developed in our Unviersity of Wisconsin study are useful for diagnosing which students have particularly problems with geologically relevant visualization skills. Our results also suggest that a small amount of time devoted to visualization practice can improve students' skills. We observed this in two ways. First, the superior exam performance by students in the experimental group on visualization-related questions suggests that the extra practice they received solving stereonet-related problems was beneficial. This observation is strengthened by the similar scores on non-visualization problems observed for the experimental and control groups. Second, the overall improvement of all students by the third exam on the visualization questions suggests that the frequent practice in the lecture portion of class was also beneficial. This is a reassuring result, suggesting that differences among individuals are not static and that major gains can be made for students with poorly developed spatial skills.

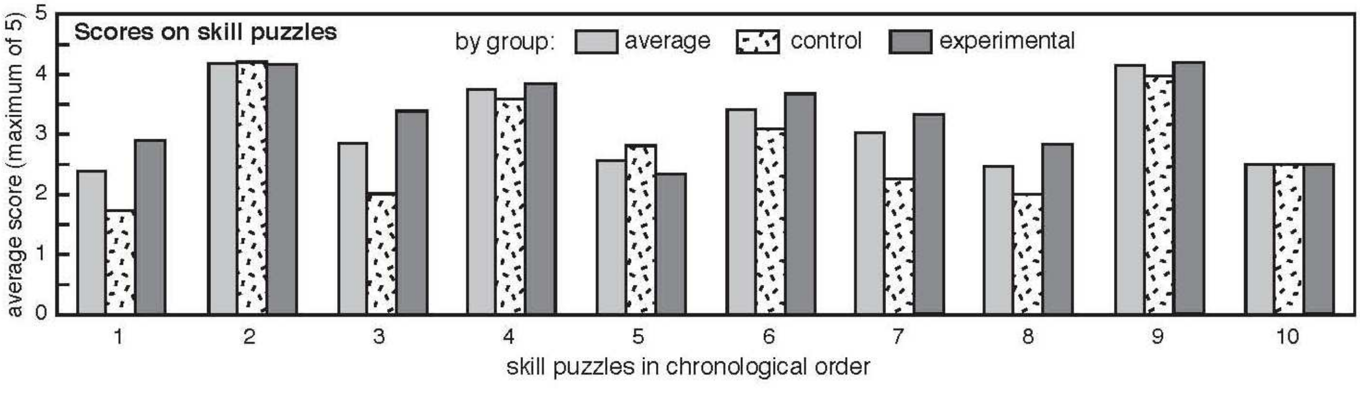


FIGURE 10. Average scores on ten skill puzzles given during Structural Geology.

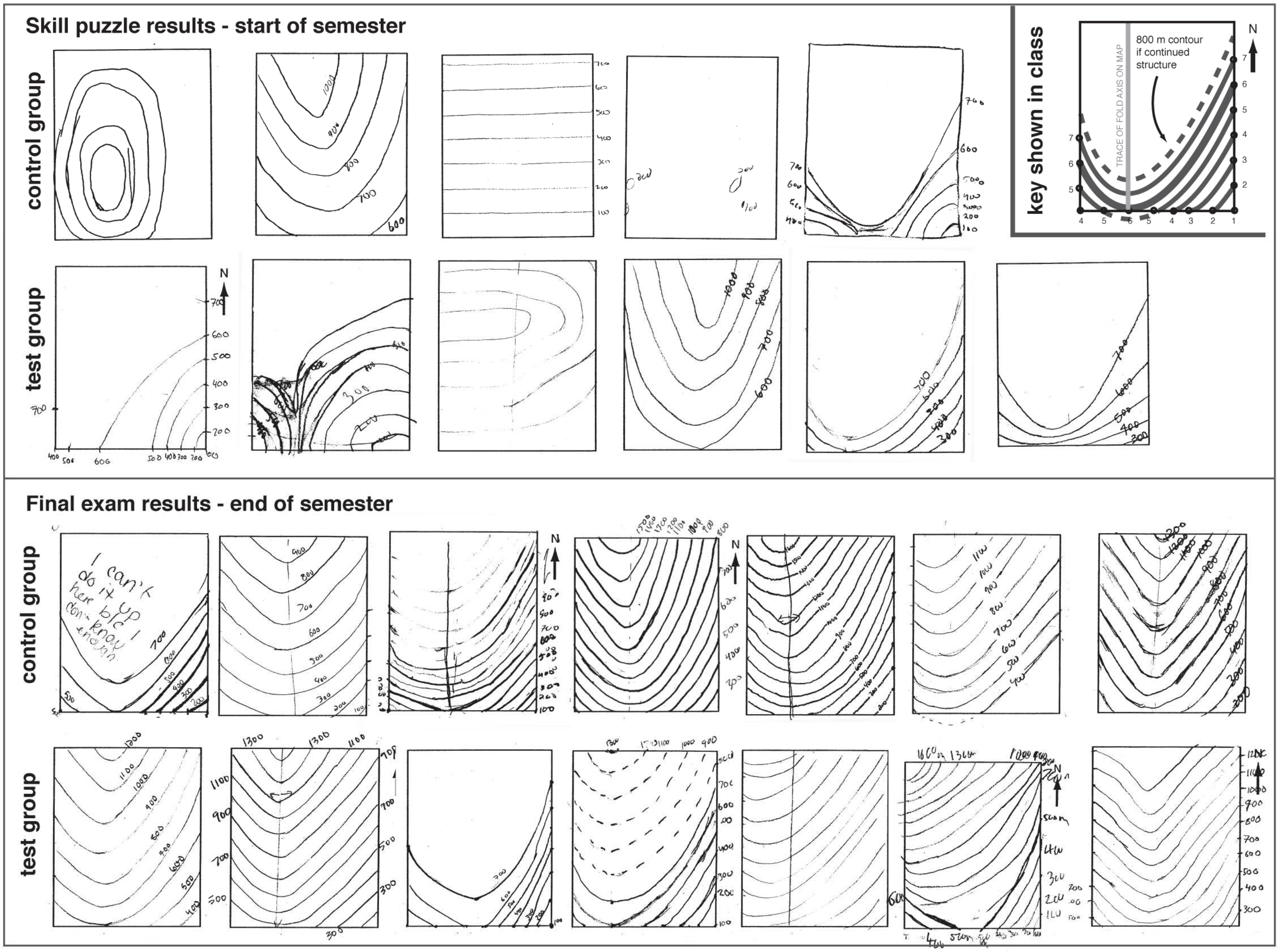


FIGURE 11. Solutions from the start of the semester (top) and end of the semester (bottom) for the skill puzzle shown in Figure 8. Note that the solution discussed after the skill puzzle was administered, shown in the upper right -hand corner, is actually less correct than many answers from the end of the survey. (The concave-up lines should actually fill the entire rectangular box.)

We recommend that instructors in highly visual disciplines use a pre-course assessment to determine the baseline spatial visualization abilities of their students. This assessment would allow educators to identify students who would benefit from extra attention devoted to developing their three-dimensional thinking skills, and students who are more likely to succeed in geoscience courses and become majors. This assessment should not be limited to a single component task (e.g. mental rotation) as this may result in a misleading, incomplete picture of students' (in particular women's) spatial visualization skills. If spatial skills are important for understanding course material, we also recommend that a small amount of class time be devoted to solving course-relevant visualization problems, as this can improve all students' spatial visualization skills.

CONCLUSIONS

In a quantitative study at Carleton College, surveys of abstract visualization skills demonstrate that there are differences in skill levels between students who are potential majors and those who are not, suggesting that students may self-select geology as a major based on their visualization abilities before significant course work. Students in introductory geology courses with very poor spatial skills are more likely to receive poor final course grades than those who have better developed spatial skills. Students' visualization skills improve in upper-level classes that require more frequent and complex spatial visualization tasks. Differences between men and women decrease in these upper-level courses as well, except for tasks requiring spatial relations (mental rotation) where men consistently outperform women.

In a qualitative study at the University of Wisconsin, we tested whether students' spatial visualization skills improved after frequent exposure to a variety of geological visualization exercises. Our instructional materials included skill puzzles given to all students in lecture and stereographic projection exercises implemented as a controlled study in lab. Comparison of exam scores between the experimental and control groups suggests that students given extra visualization practice out-performed other students on visualization questions but not on overall exam scores. These instructional materials are also useful for diagnosing when students have trouble with particular visualization skills.

Considered together, our results suggest that spatial visualization skills can be improved by participation in a geology course and by frequent opportunities for visualization practice lasting only 5-10 minutes per week.

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We invite others to use our abstract visualization survey as well as our instructional materials, which include ~20 skill puzzles (covering topics appropriate for field methods, mapping, tectonics, structural geology, and geophysics), ~10 stereographic projection exercises, and several exam questions that apply stereographic projections to different geologic problems. All exercises are available in editable digital formats and can be used either as-is or can be modified as needed by the user.

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